Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

# STUDIES FOR STUDENTS.

## DEFORMATION OF ROCKS.—III. CLEAVAGE AND FISSILITY.[1]

CONTENTS.

- Definition of cleavage and fissility.
- Development of cleavage in homogeneous rocks.
- Development of fissility in homogeneous rocks.
- Development of cleavage and fissility in heterogeneous rocks.
  - Development of cleavage in heterogeneous rocks.
  - Development of fissility in heterogeneous rocks.
- Relations of cleavage and fissility to each other.
  - Gradation between cleavage and fissility.
  - Fissility secondary to cleavage.
  - Cleavage and fissility may develop at the same depth.
- [2]Relations of cleavage and fissility to other structures.
  - Relations of cleavage and fissility to bedding.
  - Relations of cleavage and fissility to thrust faults.
  - Relations of cleavage and fissility to thickness of strata.
- Development of cleavage by other causes than thrust.
- Modifications of secondary structures.
- Application to certain regions.
- Relations of cleavage and fissility to stratigraphy.

### DEFINITION OF CLEAVAGE AND FISSILITY.

THE property of cleavage in rocks is here defined as a capacity present in some rocks to break in certain directions more easily than in others. By virtue of this property rock masses may be split into slabs or into leaves. The term cleavage is taken from a property in minerals, and is here confined to a strictly parallel usage. This definition does not agree with that ordinarily given in the text-books, but it is believed that the restriction is a gain for accurate discussion. The structure corresponds to Sorby's "ultimate structure" cleavage.[1]

---

[1] In preparing this section I am greatly indebted to a paper by L. M. HOSKINS on Flow and Fracture of Rocks as Related to Structure. Without his discussion this section would have been far more imperfect than it is. PROFESSOR HOSKINS' entire paper will appear in connection with my own full paper in the Sixteenth Annual Report of the U. S. Geol. Survey.

[2] The part of this paper covered by the contents below this point will appear in the following number of the JOURNAL.

Fissility is here defined as a structure in some rocks by virtue of which they are already separated into parallel laminæ in a state of nature. The term fissility thus complements cleavage, and the two are included under cleavage as ordinarily defined. Where a rock is finely fissile it may be called foliated. Fissility corresponds in part to Sorby's "close joints" cleavage.[3]

The terms slate and schist, slaty and schistose, slatiness and schistosity, are retained with their usual significations. A slate may be defined as a rock having the property of cleavage or fissility, or both combined, the rock parting into layers with relatively smooth surfaces. In slates the mineral particles are usually of small size. A schist is a rock having the property of cleavage or fissility, or both combined, the rock parting into layers with rough or wavy surfaces. In schists the mineral particles are larger than in slates. As is well known, there are all gradations between slates and schists. In origin and essential characters the two have many properties in common. Schistosity, however, indicates more severe metamorphism than slatiness. It follows, from the above definitions, that a slate or a schist may have the property of cleavage or of fissility or of both combined. When both are present they may be parallel or intersecting. Both may occur in the same slate or schist in more than one direction.

It is not the aim here to inquire fully as to the manner of development of cleavage and fissility. Starting with the results reached by Phillips,[2] Sharpe,[3] Sorby,[4] Tyndall,[1] Heim,[2] Daubrée,[3] Harker,[4] Becker,[5] and others, it is the purpose to inquire into the attitudes of cleavage and fissility, the causal difference between the two, and the relations which these structures have to others. The investigators mentioned have shown that cleavage and fissility are usually closely connected with folding, being one of the results of compression. It has been held (pp. 195–213) that there are great differences in the manner in which masses of rock respond to compression, depending upon depth and upon whether they are homogeneous or heterogeneous.

---

[1] On Some Facts Connected with Slaty Cleavage, by H. C. SORBY, Rept. British Association for the Advancem't of Sci., 27th meeting, 1857, pp. 92–93 of Transactions.

[2] Report on Cleavage and Foliation in Rocks, and on Theoretical Explanations of these Phenomena, JOHN PHILLIPS, British Association for the Advancement of Science, 26th meeting, 1856, Proceedings, pp. 369–396.

[3] On Slaty Cleavage, DANIEL SHARPE, Quar. Jour. Geöl. Soc. Lond., 1846, Vol. III, pp. 74–105; Vol. V, 1849, pp. 111–129.

[4] Anniversary Address of the President, HENRY CLIFTON SORBY, Quar. Jour. Geol. Soc. Lond., 1849, Vol. XXXVI, Proceedings, pp. 68–92.

Sorby explains rock-cleavage as mainly caused by the rotation of mineral particles, and especially mica, so that their longer diameters and the cleavage of the mica particles are normal to the greatest pressure. The rock readily parts along the greater dimensions and cleavage of the mineral particles. The minute mica plates were supposed to be fragmental particles deposited in the plane of bedding, and to have been rotated by the movement of the rock to a position normal to the pressure. Sorby also showed that the laminar hydrous silicates, such as chlorite, develop in situ parallel to the cleavage. He did not think that this was true of mica in slates, but believed that the parallel mica flakes of mica-schist form in situ during the recrystallization of the rock.

Sharpe and Tyndall explain cleavage as due to the flattening of the mineral particles by pressure, so that they have a parallel arrangement with their shortest axes in the direction of greatest pressure. This cause and the causes given by Sorby have ordinarily been regarded exclusive of each other, but it is believed that they may be mutually supporting.

---

[1] The development of Slaty Cleavage, JOHN TYNDALL, Philosophical Magazine, 4th Ser., Vol. XII, pp. 35–48, 1856.

[2] Mechanismus der Gebirgsbildung, ALBERT HEIM, Band II, 1878, pp. 51–74, mit einem Atlas.

[3] Géologie Expérimentale, by A. DAUBRÉE, Vol. I, pp. 391–432, Paris, 1879.

[4] On Slaty Cleavage and Allied Rock Structures, with Special Reference to the Mechanical Theories of their Origin, ALFRED HARKER, British Association for the Advancement of Science, 55th meeting, 1885, Proceedings, pp. 813–852.

[5] Finite Homogeneous Strain, Flow, and Rupture of Rocks, by G. F. BECKER, Bull. Geol. Soc. Am., Vol. IV, 1891, pp. 13–90.

My microscopical study of both cleavable slates and schists has convinced me that in the interstices, and by the decomposition of the larger particles, new minerals, and especially mica, abundantly develop with similar orientation and with their longer diameters or cleavage, or both, parallel to the flattened or rotated original particles. The innumerable parallel minute flakes of cleavable minerals in slate, especially mica and chlorite, which are almost universally present, are in no case detrital, so far as observed by me, but have developed in situ. Usually it is easy to discriminate the large, comparatively sparse, fragmental mica plates, if any are present, from those which are autogenic. As soon as a new mineral particle has developed it is subjected to flattening and rotation precisely as is an original mineral particle. This parallel arrangement of minerals developed in situ is probably the most important single cause of cleavage.

Not infrequently unmodified igneous rocks have the property of rift or cleavage more or less perfectly developed. In all cases observed by me this capacity is due to the arrangement of the mineral particles with their longer diameters in a common direction or to their similar crystallographic orientation, or both. In the case of cleavable minerals, the particles which are similarly oriented give the rocks a capacity to part parallel to the direction of readiest mineral cleavage, and this tendency is more marked if the greater dimensions of the mineral particles accord with their cleavage. In some cases, in which there is a rift in two directions, this is due either to cleavage in the mineral particles in two directions or to cleavage of them in one direction and their parallel arrangement with longer axes in the other direction. Hornblende is one of the minerals which sometimes produces a cleavage by having very numerous crystals with their longer diameters in a common direction. Feldspar is one of the minerals which produces cleavage on the same principle as hornblende, but which also in some cases gives a rock-cleavage as a result of the cleavage of the mineral particles.

From the foregoing it is believed that *rock-cleavage is due to the arrangement of the mineral particles with their longer diameters or readiest cleavage, or both, in a common direction, and that this arrangement is caused, first and most important, by parallel development of new minerals; second, by the flattening and parallel rotation oj old and new mineral particles; and third, and of least importance, by the rotation into approximately parallel positions of random original particles.* The propriety of the definition of rock-cleavage as first given is therefore evident. It is always due to a capacity to part, and very frequently the parting does occur by the actual cleavage of the mineral particles.

### DEVELOPMENT OF CLEAVAGE IN HOMOGENEOUS ROCKS.

Becker has recently rediscussed the origin of cleavage, and concludes that it always develops in the shearing planes rather than in the normal planes. Even in the case of the experimental development of a cleavage-structure in wax, which is strictly normal to the pressure, the structure is explained as developing in the shearing rather than in the normal planes.

As will be seen below, it is my own conviction that a structure develops in the normal planes under certain conditions, and that under other conditions structures develop in the shearing planes, as advocated by Becker. The first is believed to be a deep-seated phenomenon of the zone of flowage; the second is believed to be a more superficial phenomenon in the zone of fracture. In other words, as already stated, it is thought that under the term cleavage two entirely distinct structures of different origins have been confused. Theories which explain or partly explain one of these structures have been extended to cover both of them, because it was not understood that they are different.

Rocks when deformed under great weight flow as a plastic solid, and under these circumstances, as shown by the geologists above cited, the property of cleavage is developed. At all times the particles of the rock are welded together. Fissility will not form, for by the supposition the rocks are so deeply buried that no crevices can exist. In the formation of flowage cleavage, or cleavage proper, as the term is here used, the thrust may be from one or more than one direction. It may vary in force both horizontally and vertically. In any case there is flow of the rock-mass in the direction of least resistance. If the force be applied so that there is uniform shortening in one direction, as in the case of a rigid piston, the elongation is at right angles to the direction of thrust, or in the normal planes. This may be called *pure shortening* (Figs. 1 and 2). By pure shortening is meant the particular kind of non-rotational distortion illustrated. The volume remains unchanged, the shortening in one direction being compensated by equivalent elongation at right angles to this. In this kind of deformation, while there is no differential movement or shearing in the normal planes, shearing does occur along all of the intersecting diagonal planes. It makes no difference whether the movement is wholly from one end of the mass or in part from both ends. But when the lateral force varies greatly at varying depths the deformation may vary from pure horizontal shortening to a nearly horizontal differential movement combined with shortening (Figs. 5 and 6). Such inclined differential movement is dependent both upon the varying force of thrust in passing from higher to lower horizons and upon increased friction with greater depth, due to gravity, which acts as an opposing force. In the case last illustrated the deformation is a simple shear.[1] The deformation here called pure shortening is defined by Becker[2] as a shear, and a shear, as just defined, is called by him scission.

Ordinarily, at any place in the rock-mass the three principal compressive stresses are unequal. If the differential stress surpasses the elastic limit of the rock it produces shortening in the direction of greatest stress, elongation in the direction of least stress, and shortening or elongation in the direction of mean stress, depending upon whether the latter is nearer the maximum stress or the minimum stress. The phenomena subsequently described appear to show that there is more frequently elongation than shortening along the direction of mean stress. It follows that as a result of flowage there is usually one direction of shortening and two of unequal elongation. The plane of the minimum and mean stresses is believed to be the plane of cleavage.

---

[1] Text-book of the Principles of Physics, by Alfred Daniell, 3d edition, 1894, p. 78. Macmillan & Co., London and New York. Elementary Text-book of Physics, Anthony and Brackett, 4th ed., 1888, pp. 113–114. Treatise on Natural Philosophy, Thompson and Tait, new ed., 1890, Part 1, pp. 123, 124.

[2] Finite Homogeneous Strain, Flow, and Rupture of Rocks, by G. F. Becker, Bull. Geol. Soc. Am., Vol. IV, 1891, pp. 22–25.

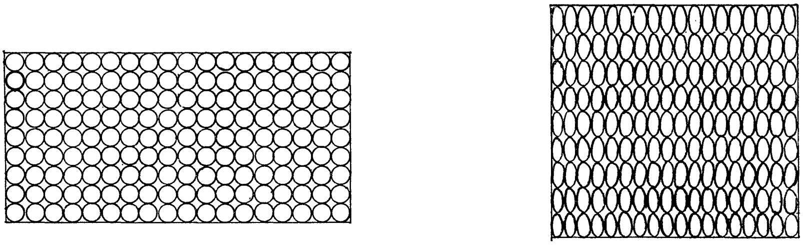

FIG. 1 FIG. 2

Figs. 1 and 2. Showing theoretical change in arrangement and form of particles when uniformly shortened by hydrostatic viscous flow.

A coherent slate, which has the unmodified property of cleavage as here defined, shows but a single marked structure. This structure in the dense slates is often nearly normal to the direction of the greatest shortening of the strata. In the many instances in which cleavage is everywhere nearly parallel to intrusive igneous masses, there seems to be no escape from this conclusion. In such cases a zone of slate or schist surrounds a granite or other mass, the secondary structure varying in direction through 360°, thus making a circle about the intrusive core. The cleavage is therefore at each point nearly at right angles to the greatest pressure. Such zonal cleavage about batholites has been described in this country at various localities. The cleavage in the mica-schist adjacent to the granite core of the Black Hills is everywhere parallel to the igneous mass. Lawson has described like phenomena at many places in the mica-schists of Ontario. The secondary structure is everywhere parallel to the adjacent igneous masses. Emerson finds that the same relations obtain between the secondary structure and the intrusive granites in Massachusetts. Similar phenomena have been described in other countries at localities too numerous to mention. In all of these cases there can be no doubt that the magmas were under hydrostatic conditions and transmitted their pressures at every point normal to the rocks with which they were in contact. There would therefore seem to be no escape from the conclusion that in such cases the secondary structure developed in planes normal to the pressure.

In homogeneous slates having cleavage it is not usually possible to follow the particles through their movements to their final positions. However, in rocks which are not so nearly homogeneous there are numerous minor plications. Where these plications are arranged in a symmetrical fashion, that is, do not have one set of limbs longer than the others, they give strong evidence that the thrusts were in opposite directions and normal to the secondary structure. If the rock were homogeneous the crumplings would disappear and the movement of the particles would more nearly follow the law of plastic flow. Such deformation of the particles may be without differential movement normal to the pressure, and is illustrated by Figs. 1 and 2 in an ideal case. It is not necessary that the particles be of the same size or of the same strength. As is known by macroscopical study of the schist-conglomerates and by microscopical study of ordinary slates and schists, if the movement continues far enough the old mineral particles are flattened, or flattened and rotated, into parallel positions. New minerals develop with similar orientation. Therefore, as a consequence of the flowage of the stratum, the induced arrangement of the particles necessarily produces a capacity to cleave in the plane of the two longer axes of the mineral particles, as in this direction the rock may part between them.

In the case of forces resulting in rotatory movement, the structure may be explained as developing in the normal planes as in the case of pure shortening. The direction of shortening of any small area varies in its relation to the component particles at each successive moment. This variation may be due to the work of stress-couples producing simple shearing, to a change in the direction of pressure, or to a rotation of the area concerned, or two or all combined. The final result, as shown by Professor Hoskins, is to deform a given homogeneous area as though it were shortened in but a single direction, and after this was rotated (Fig. 3). The cleavage is at right angles to the direction of greatest shortening of the area in its final position, this structure being due to the capacity to part parallel to the greater dimensions of the mineral particles. This resultant position is not normal to the final direction of greatest pressure, but at any given moment the deformation occurring is itself normal to the pressure. Newly developing minerals also tend to form at any moment with their shortest axes in the direction of pressure, and are rotated by the simple shearing exactly the same as the original minerals. Therefore the shortest axes of both new and old minerals are in the same direction. Thus the cleavage develops strictly in the normal planes, but its position by the rotation of simple shearing is inclined to the final direction of pressure.[1]

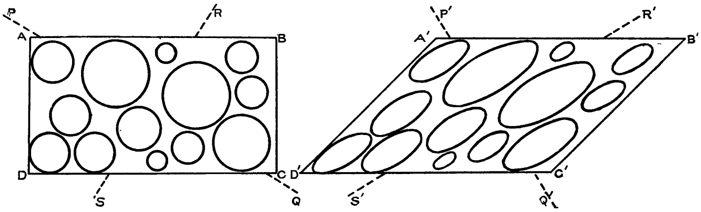

FIG. 3.—A portion of a bed *ABCD*, containing round pebbles, is shearing into the form *A′B′C′D′*. The cleavage is parallel to *R′S′*. The result is the same as through the material had been flattened by pressure along *PQ*, and the mass afterwards rotated until *RS* fell in line with *R′S′*. After Hoskins.

---

[1] It is admitted to be somewhat difficult to understand the precise nature of the ultimate interior movements by which pure shortening involving shearing along two sets of intersecting diagonal planes produces a structure normal to the greatest pressure. However, Professor Hoskins shows that during pure shortening it is only for a moment that any given plane is one of maximum tangential stress and pure sliding, and that all planes inclined to the greatest pressure are shearing planes (Figs. 1 and 2). If some structure should be produced along the shearing planes in the zone of flow, one would not expect a structure in a single direction, but structures in an indefinite number of direc-

I therefore conclude from analysis, from experiments upon viscous and plastic bodies, from observations in the field, and from studies with the microscope, that I am justified in the statement that *the secondary structure of a rock which is deformed by plastic flow develops in the plane normal to the greatest pressure, and that this structure is true cleavage.*

We thus see that in both the case of pure shortening and the case of shortening combined with rotation the secondary structure is parallel to the greatest dimensions of the mineral particles. This parallelism may be macroscopically observed at very numerous localities in which schist-conglomerates occur. Some of the more important of these are the Hastings district of Ontario, Green Mountains of Vermont (Fig. 4), Felch Mountain district of Michigan, many localities in the basal conglomerates of both the Upper Huronian and Lower Huronian in the Marquette district of Michigan, the Black Hills of Dakota, and the Front Range of Colorado.

In different localities the degree of flattening of the pebbles varies from a small amount to that in which the pebbles are

tions. In most cases where a solid mineral particle or an aggregate of mineral particles having an individuality is much flattened, we have evidence of the very complicated shearing along many intersecting planes. The deformation, if carried far enough, ordinarily does not produce a single, or even two structures, but complete granulation. The sum total of the sliding along all of the shearing planes is to shorten the diameter of any given area in the direction of greatest pressure and to elongate it at right angles to this. During this deformation a given mineral particle may have become a multitude of mineral particles. However, the multitude in the aggregate differs in composition and consequently in strength from the adjacent similarly flattened areas. Moreover, many of the newly formed individual particles have similar forms in like positions. Oftentimes the readiest cleavage of many of the particles accords with their greater diameters. The result is that there is an easy parting or cleavage along the greater dimensions of the flattened areas and the greater dimensions of the newly developed particles. Even if the material is absolutely homogeneous so far as we can discover, the same principle applies, as shown by Tyndall for wax. Analogous to this is the case of stretched or compressed viscous Canada balsam, which takes on a structure not in the shearing planes, but parallel to the tension or at right angles to the pressure, as shown by polarized light. As shown by Professor Hoskins, the case of simple shearing does not differ from that of pure shortening except in that the mass as a whole is rotated (Fig. 3). If the above is true, it is clear that all combinations of pure shortening and of simple shearing in the zone of flow result in producing a cleavage which develops normal to the greatest pressure.

transformed into leaf-like areas. Everywhere and in all grades of change the secondary structure accords with the longer diameters of the flattened pebbles. The some phenomena have been observed by me in microscopical studies upon fragmental particles in hundreds of sections from the semicrystalline formations from many parts of America.

According to Becker's explanation of slaty cleavage, there is an important discrepancy between the direction of the structure and the greater diameters of the flattened mineral particles.[1]

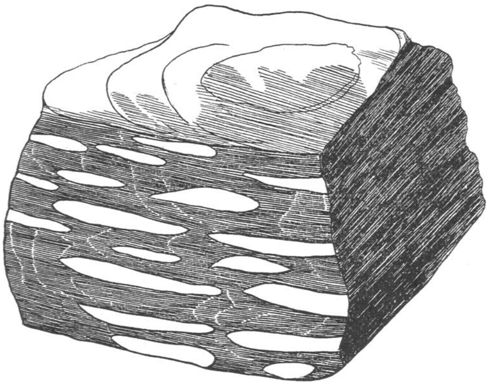

FIG. 4

Fig. 4. Schist conglomerate, showing pebbled character when cut transverse to the major direction of shortening, and gneissoid character when cut in other directions, from Plymouth, Vt., after Hitchcock.

If the above observations are correct, it would seem that there is no escape from the conclusion that the secondary structure which I here describe as cleavage is not developed in the manner described by Becker and cannot be explained by his theory. I therefore return to the old explanation of the English geologists—which perfectly accords with the facts—that this secondary structure develops in planes normal to the pressure.

In further confirmation of this explanation are certain phenomena described to me by Diller and Keith.

Diller makes the following statement:

---

[1] Finite Homogeneous Strain, Flow and Rupture of Rocks, GEORGE F. BECKER, Bull. Geol. Soc. Am., Vol. IV, pp. 55–66.

> At Crystal Lake, on Hough's Peak, Plumas county, California, is a conglomerate that is immediately associated with slate. Slaty cleavage is well developed in the latter, and also in the conglomerate. The greater diameters of the flattened pebbles are always in the cleavage planes. The harder pebbles are less elongated than the softer ones, and are frequently fractured, the fractures being diagonal to the cleavage.

The probable explanation of the phenomena is that the cleavage develops in the normal planes and the fractures develop in the shearing planes, as explained by Becker. At the same depth and pressure the softer parts of the rock were under conditions of flow and the hard pebbles under conditions of fracture.

Keith makes the following statement:

> Near Blowing Rock, N. C., is a mashed porphyritic granite in which porphyritic crystals of feldspar are flattened in various degrees, and their greater diameters are upon the average parallel with the secondary structure. In many cases the feldspar crystals are fractured in a direction diagonal to the cleavage, and in some cases in a single feldspar crystal there are two sets of diagonal fractures approximately at right angles to each other and each inclined about 45° to the cleavage.

The phenomena therefore correspond precisely to the idea of a pressure normal to the cleavage, which at the same time produced fractures in the more rigid feldspar crystals along the maximum shearing planes. As in the slate described by Diller, the weaker matrix was under conditions of flowage at the same depth that the more rigid feldspar crystals were under conditions of fracture.

It is a very common phenomenon in slates and schists, both macroscopically and microscopically, for the direction of the secondary structure to wrap around the harder particles. As a hard grain or pebble is approached the cleavage structure in the matrix opens out on each side of the grain, envelops it, and closes in again beyond it. The structures nowhere intersect, although upon opposite sides of a particle near the ends they converge, and in passing toward either end they turn and become parallel. They would intersect if continued in their original direction. While the cleavage of the matrix, where there are many harder particles, constantly varies in direction, it nowhere intersects. Its average direction is the same as that of other parts of the rock in which resistant particles are absent. Because the structure of the cleavage, where hard particles are present, simulates a mesh structure, loose observation might lead to the conclusion that there are present two intersecting structures. The prime characteristic of a true mesh structure is that two diagonal structures shall intersect. As shown subsequently (p. 465), interesting diagonal fissility may develop in the shearing planes.

The deviation of cleavage about hard particles is explained by the fact that the more resistant grains act as transmitters of forces. At any given point at the exterior of a hard particle the direction of greatest pressure is normal to the grain, and hence the peripheral arrangement of the cleavage about the grain. The principle is precisely the same as that explaining the development of zonal cleavage about intrusive batholites. (See pp. 455–456.)

The crucial point in deciding whether there is a structure which develops in the normal plane is the simple matter of fact as to whether or not the flattening of the original particles corresponds with this structure. In testing this point it is best to take examples in which the flattening of the particles is not too great (see Fig. 4), else the lessening discrepancy between a possible structure called cleavage by Becker,[1] developing in the planes of "maximum tangential strain," and that regarded as cleavage by me, developing in the normal planes, may be overlooked. As already explained, I hold that the facts of the field accord with my position. Upon this crucial point of fact I ask the observation of geologists, for by the facts of occurrence must be judged the adequacy of the explanation offered as to the manner of action of the forces which produce cleavage. It is believed by me, as will be seen, that the theory that cleavage is developing at any given moment normal to the pressure fully explains all the diverse facts of true cleavage in both homogeneous and heterogeneous rocks.

[1] Finite Homogeneous Strain, Flow and Rupture of Rocks, GEORGE F. BECKER, Bull. Geol. Soc. Am., Vol. IV, pp. 55–66.

The amount of shortening of the area of a rock-mass necessary to produce the property of cleavage may not be great in a slate, as shown by the amount of distortion of the bedding. In proportion as the shortening becomes greater the rock is apt to change from a slate to a schist. If the process of shortening continues until a schist is produced, it is often difficult or impossible to estimate the amount of horizontal shortening of the strata, but it is certain from observation that it is usually considerable, perhaps to one-half or one-third of the original. This is shown by the plications of layers of a slightly different color which are cut by the schistosity. If plicated layers such as often occur in schists were straightened out, they would require a distance across the schistosity two or three times as great as at present.

It is very rare indeed that any rock is so homogeneous that the unmodified law of normal flow perfectly applies as above given. Among the sediments argillaceous rocks most nearly approach homogeneity. The massive rocks, however, still more nearly approach homogeneity. But even these are not strictly homogeneous, being composed of mineral particles of different sizes and characters. However, these particles in many instances are uniformly flattened and readjusted, so that the mass in a large way almost perfectly obeys the law. A mashed massive rock having cleavage but not fissility is a solid, strong schist, and it is in this class of rocks that cleavage in a uniform direction as the result of normal plastic flow is best exemplified.

Rarely rocks show an almost equal capacity to part in any direction parallel to fibers. In these cases the microscope shows that the mineral particles are very long in the fibrous direction, and have about the same average magnitude in all directions at right angles to their greatest diameters, instead of having two definite directions of mean and minimum diameters at right angles to each other, as is ordinarily the case in slaty cleavage. As pointed out by Professor Hoskins, this structure is explained by the deforming or maximum pressure being equal or nearly equal throughout a circle of revolution in all directions perpendicular to the fibrous structure and by less pressure in the direction parallel to the fibers. This results in shortening in all radial directions and elongation at right angles to this, and thus the fibrous structure is formed normal to the plane composed of the radial direction of greater pressure.

It has been seen on a previous page that unmodified igneous rocks may have the capacity to cleave, and that the structure is similar to a secondary structure in sedimentary rocks. There is not so great a difference between the two in this respect as might at first be supposed. The arrangement of the mineral particles in the igneous rocks is caused by the similar original crystalline orientation of the mineral particles produced by unequal stresses in three dimensions and by the rotation of flowage. In the sedimentary rock the same is true, but the flatness of the particles is due to another cause. The chief difference is, however that the lava is a viscous liquid and the crystallized rock a plastic solid. The manner in which the parallel minute mineral particles which produce cleavage in igneous rocks change their direction in passing around a large porphyritic crystal is as similar as possible to the way in which laminar mica scales in a slate or schist change in direction in passing around a large refractory grain. In both cases the material wraps around the rigid particles which were sufficiently strong to partially or wholly resist deformation.

The above explanation of cleavage makes this structure also analogous to the capacity to part along bedding planes in sedimentary rocks. As each erosion particle has unequal diameters, it comes to rest in most cases with its longer diameters in the plane of bedding, thus giving at the outset a laminated structure. This structure may be emphasized by the pressure of gravity. It therefore follows that the unaltered sedimentary rock ruptures more readily along its bedding plane than elsewhere. That the capacity to part parallel to bedding is less marked than parallel to the cleavage of slates and schists is due to the fact that the ratio of the minor to the mean and major diameters of the mineral particles is not so large and the regularity of the parallel arrangement not so nearly perfect in the original sediment as in a slaty or schistose rock. If a maximum deforming force be normal to the bedding, as it may be in some cases, the original imperfectly parallel arrangement of the mineral particles, with their longer axes in the direction of bedding, would be so much done toward producing a cleavage, and the result would be to give a more highly developed secondary structure parallel to the bedding with a given amount of movement than would result from the same deformation in a different direction.

In some instances, as has been seen, observations show that the conjoint action of tangential thrust and friction throughout considerable masses of rocks was apparently such as to give approximately uniform shortening of the strata in one direction. The material is confined on all sides, and its deformation is that of a plastic solid. The direction of least resistance is toward the surface of the earth. The direction of mean resistance is at right angles to the minor thrust and parallel to the surface. Consequent upon the flow, the mineral particles, new and old, at any particular point arrange themselves with their longer axes in the plane of these directions. This plane is vertical, or nearly so, and almost at right angles to the major thrust. Therefore, in approximately homogeneous rocks cleavage is frequently vertical or highly inclined, and hence intersects the bedding. This may be called *cross cleavage.*

But supposing the lateral thrust to vary greatly in depth, and considering that friction increases with depth, the movement may vary, as explained above, from upward plastic flow to differential movement in a horizontal direction. In this change we have passed from a pure shortening to a simple shearing. If the movement was sufficient the cleavage would be nearly parallel to the bedding, and it may be called *parallel cleavage.* In the case of parallel shear the cleavage would accord in its principle of development with that of parallel cleavage in heterogeneous rocks, subsequently described (see pp. 472–480).

These extreme cases rarely occur. Almost invariably there is a combination of pure shortening with shearing motion. The combination is ordinarily such as to give steeply inclined cleavage cutting the bedding, and therefore a cross cleavage. There are, however, undoubted gradations between cross cleavage and parallel cleavage. In all cases in nature the final resultant or direction of movement depends upon a union of all the forces concerned.

### DEVELOPMENT OF FISSILITY IN HOMOGENEOUS ROCKS.

If a rock be in such a position and under such conditions that it is deformed by regular fracture, it is probable that the secondary structures form in the shearing planes. Just as in the case of cleavage, at any place in a rock-mass the three principal stresses are usually unequal. In the zone of fracture if the differential stress surpasses the ultimate strength of the rock, fracture occurs along the two sets of shearing planes which incline toward the greatest stresses and are parallel to the minimum stress. The planes of maximum shearing stress in the case of normal pressure are 45° from the greatest pressure and are at right angles to each other, but Hoskins shows that the fractures may incline at a smaller angle than this to the direction of greatest pressure, the latter bisecting the acute angle made by the intersecting ruptures. It is only in case the two lesser stresses are equal, or nearly so, that concoidal fractures are produced, such as occur in ordinary building-stone tests of cubes. In this experiment there is one direction of great stress and two directions at right angles to this of very subordinate equal stress.

Hence, in the zone of fracture, where the differential stress surpasses the ultimate strength of the rock, there may be produced a fissility in two sets of intersecting planes equally inclined to the greatest pressure. It is well known that a fissility in two directions occurs in many homogeneous rocks, and such structures have doubtless developed along the shearing planes under this law.

In case the direction of greatest normal pressure is nearly horizontal, the planes of fissility would be at angles of about 45° with the horizon. However, as no rocks are strictly homogeneous, and as the direction of greatest normal force is always compounded of thrust and gravity, the directions of the fissility may vary considerably.

In case the parting is very close, the rock is foliated. Each lamina moves slightly over the adjacent laminæ. The rubbing of the laminæ over one another, due to the differential movement, gives the slickensided surfaces which are so common on both sides of the parted laminæ. The more intense the movement, the thinner and more brilliant do the folia become. Since partings are usually inclined to the bedding, this structure may be called *cross fissility*.

In passing from the zone of fracture to the zone of flow it is to be expected that all gradations would be found between the development of cleavage in the normal planes and the development of fissility in the shearing planes. This point is discussed later. (See pp. 480–481.)

Frequently fissility forms in lithologically homogeneous rocks in which the property of cleavage had already been developed, and which by subsequent denudation are brought so near the surface that the superincumbent weight is less than the strength of the rocks. When subjected to stress under these circumstances numerous fractures develop along the cleavage planes. This occurs because fractures take place so readily along these planes, and because the chances are always that these are shearing planes, although they may not be those of maximum shearing stress.

This may be the case although the direction and force of thrust may not have varied. The direction of greatest normal pressure, combined of gravity and thrust, would be in a different direction when the rocks are in the deep-seated zone of flowage and when they are in the superficial zone of fracture. Thus, cleavage in the normal planes would pass into the shearing planes as denudation progressed.

In cases in which the fissility develops along a prior cleavage, the fissility parallel to these planes would be marked. The fracturing along the other set of diagonal shearing planes, not having the advantage of a previous cleavage, would be much less marked, the deformation perhaps largely occurring by considerable movements along a few planes of shearing. In this case the infrequent cracks may properly be called joints. In the planes of fissility secondary to cleavage the folia slip over one another just as in the case of originally developed fissility independent of cleavage, producing slickensided surfaces, and the rock develops a "fault slip" cleavage or "ausweichungs" cleavage. In the majority of cases in which the fissile laminæ are close together and have a uniform direction for a considerable area, it is probable that the structure first developed as true cleavage in the normal planes, and that a later movement, when the rock was nearer the surface, developed the fractures along the shearing planes. The structure is thus a product of the forces producing cleavage and those producing fissility working successively under different conditions.

As will be seen below, fissility may form, in a manner similar to its development parallel to cleavage, parallel to planes of weakness of any other kind, as, for instance, bedding.

The directions of the fissility are therefore dependent upon the direction of the forces, upon whether they are equal or unequal, upon the superincumbent load and the consequent friction, upon the cleavage and other previous structures, and upon previous folding.

If fissility develop along cleavage, as this structure is usually steeply inclined, the fissility will be in the same direction. That great thrust faults sometimes develop with nearly horizontal hades, or even parallel to bedding, is well known. Multiple minor thrust faults or fault slips producing fissility may similarly develop with flat hades, upon the same principles as cleavage, in a like direction, and thus produce a fissility nearly or quite horizontal, or parallel to bedding. It is therefore clear that the structure may vary from a vertical to a horizontal attitude. There are therefore all gradations between cross fissility and parallel fissility, described in the following number (Fig. 7), just as between cross cleavage and parallel cleavage. In the case of parallel fissility the movement may be compared to the differential movements of a ream of paper which under load is pushed unequally forward from one end, the differential movement between any two successive sheets being the same. While the bottom sheet may be shoved one-tenth of an inch, the top sheet may be shoved 10 inches (Figs. 5 and 6). Between the bottom and the top the amount of forward movement would vary regularly from one-tenth of an inch to 10 inches. While the differential movement between any two sheets is the same, each sheet gains all the forward movement of all the sheets below.

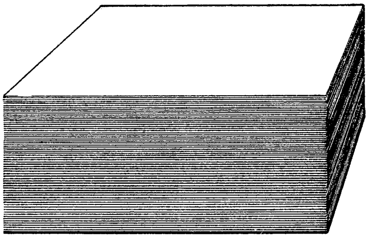

FIG. 5

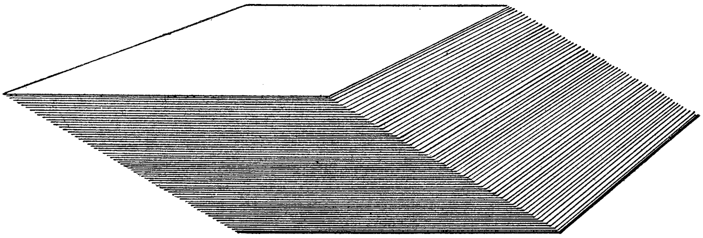

FIG. 6

FIGS. 5 and 6.— Theoretical deformation of laminated rock by uniform differential movements parallel to a previous structure.

Where fissility develops, either as an original or secondary structure, rubbing usually occurs between the mineral particles along the sides of the laminæ. As a result, the minerals receive an elongation in the direction of greatest movement, a less elongation in the direction at right angles to this and in the plane of movement, but are shortened at right angles to the plane of movement. Also new minerals which develop are controlled in the same manner. If the fissility be secondary to cleavage, the minerals were previously oriented with their two longer axes in the plane of differential movement, and the slipping of fissility but emphasizes an arrangement of the mineral particles which already existed.

### DEVELOPMENT OF CLEAVAGE AND FISSILITY IN HETEROGENEOUS ROCKS.

When a set of layers, either sedimentary or not, of different lithological character are folded, and cleavage or fissility develops in them, the process is not simple.

As the case of alternating sediments is the most important one, and somewhat different from any other, this will be first considered.

The original series, instead of being homogeneous, is composed of beds of different characters; that is, it consists of alternations of mud, grit, sandstone, limestone, etc. Before these rocks are folded the forces of consolidation, cementation, and metasomatism may have been at work. As a result of these prior alterations, combined with original deposition, the strata may have greatly varying strength. The sandstones may have been transformed to quartzites; the grits may have been changed to graywackes; the muds may have been compacted into shales; and the limestones may have become crystalline.

When such a series is folded the accommodations occur mainly along the beds. The greatest readjustments and greatest compression are along the limbs of the folds (see pp. 207–210, and Figs. 2, 3, and 5 of my first article). Each layer shears over the one next below under enormous stress. The necessary movement at first is largely concentrated in the weak layers between the beds of stronger material (Fig. 7). The shearing extends from these into the harder ones, for when motion has once begun along a certain set of planes, that very movement weakens the rocks along these planes and makes it easy for the forces applied in any direction to be decomposed into forces producing further movement along the same planes.

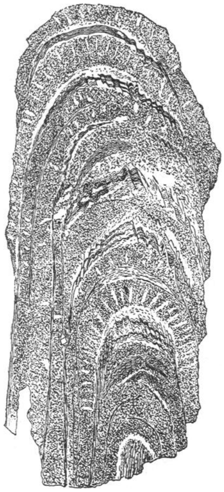

FIG. 7

Parallel fissility on the limbs of the folds and cross fissility on the anticlines, and gradations between the two. After Heim.

The deformation is mainly by folding, but on the anticlines, where the material is partly relieved from stress, the deformation is partly by multiple minor faulting.

The maximum force producing shear is composed of horizontal thrust and gravity, and its direction will therefore usually be inclined to any layer in a horizontal position, although if gravity is unimportant as compared with thrust this inclination may be slight. When the layers become tilted this inclination is marked, although the problem becomes more complicated on account of the strength of the individual beds. These tend to decompose the forces which they receive at one point into components parallel and normal to themselves, and transmit the longitudinal thrust to another point. Upon the limbs of the folds the beds are, however, never free from superincumbent weight, and the rigidity of the overlying beds must also be often overcome. Therefore, in nearly all cases of heterogeneous rocks the direction of greatest normal stress is inclined to each layer. There are two classes of cases — those in which the rock bed is in the zone of flowage, and those in which the rock bed is in the zone of fracture. The first afford conditions for the development of cleavage; the second, those for the development of fissility. Between the two there may be gradations.

### DEVELOPMENT OF CLEAVAGE IN HETEROGENEOUS ROCKS.

For a given very small area in a stratum the cleavage may vary from parallel to perpendicular to the bedding. If at any moment the direction of greatest normal pressure is in the direction of bedding, the secondary structure will tend to develop at right angles to the bedding. If, on the other hand, the direction of greatest pressure is at right angles to bedding, the cleavage will tend to develop nearly parallel to the bedding. Between these two there will be all gradations. For different beds and for different areas in the same bed the direction of greatest pressure will, at successive times, vary both relatively and absolutely, and therefore the cleavage developing in the normal planes at any given moment will gradually vary in direction. For a small, practically homogeneous area the final resultant will be the same as in homogeneous rocks (p. 457)—that is, the cleavage will be perpendicular to the direction of greatest final shortening.

Having made this general statement, let us inquire more particularly how the forces producing cleavage act in heterogeneous rocks.

As a result of the folding, combined with denudation, the relative amounts of thrust and gravity vary at different times, so that the average direction of greatest normal pressure for a given area also varies. On account of the differing strength of the beds the forces received by them are decomposed to a greater or less degree into directions parallel and normal to themselves, and thus the direction of greatest pressure is varied at each particular point. During the folding process the inclination of the beds is constantly changing, and as a consequence any given small area is being rotated with reference to the direction of greatest pressure. The problem is further complicated by the readjustment between the beds, which constantly changes the relative position of the material with reference to the pressure. Lastly, the readjustment usually takes place mainly within the weaker layers, and this changes by a varying amount the relative positions of different parts of the beds with reference to the greatest pressure. At any given point there will be a plane in which are the major and mean axes of the mineral particles, and this will be the plane of cleavage. It is evident that this plane will vary in position from place to place. As shown by Professor Hoskins, these conclusions follow from the fact that all of the different compressions, acting in different directions at different times, are equivalent to some single compression acting continuously in one direction, and the shearing motion of differential movement is equivalent to a compression combined with a rotation.

Very frequently the position of the cleavage with reference to the bedding for a given small area will be controlled by the readjustment between the beds. The structure will tend at any moment to develop in the normal planes, but as a consequence of the shearing the material is rotated so that the final direction of cleavage is inclined to the direction of greatest pressure (see Fig. 3). Since the readjustment is mainly concentrated within the weaker layers, the structure may be so rotated in them as to approach parallelism with the beds, while in the adjacent stronger beds, in which there is less differential movement, the structure may be nearly at right angles to the beds ; and at various positions between the cleavage will have intermediate directions. There will thus be developed a cross cleavage in the more resistant beds, which varies by a gentle curve into parallel cleavage in the weaker beds. On opposite sides of the layer the curves are in opposite directions (Fig. 10). By these curves it is easy to determine the relative directions of the movements of the layers.

Directly following from the above we have the explanation of the step cleavage[1] of the older authors and of Becker,[2] and of the differential cleavage of Dale. In this case the change in the direction of cleavage, instead of being gradual, as it is in rocks of gradually varying plasticity, is somewhat sudden in passing from one bed to another differing in rigidity. As a result of the shearing motion the cleavage is rotated more in the more plastic layers and less in the less plastic layers. Hence, *in heterogeneous rocks having cleavage, in a soft layer the cleavage more nearly accords with beading than it does in a hard layer.*

---

[1] On Slaty Cleavage and Allied Rock Structures, with Special Reference to the Mechanical Theories of their Origin, ALFRED HARPER, Brit. Assoc. Adv. Sci., 55th meeting, 1885, Proceedings, pp. 829–830.

[2] Finite Homogeneous Strain, Flow, and Rupture of Rocks, GEORGE F. BECKER, Bull. Geol. Soc. Am., Vol. IV, pp. 84–87.

To summarize: We have the absolute direction of greatest pressure varying; as a consequence of the difference in the strength of the beds we have the direction of greatest pressure varying from place to place; we have the material of any given area on the limbs of folds rotated with reference to the direction of greatest pressure; and finally, we have variable differential motion between the beds, which momentarily changes the direction of the area with reference to the pressure. However, Professor Hoskins shows that these all combine to produce at any given point a shortening of the particles in one direction and an elongation in one or both directions at right angles to this. Newly developed mineral particles have similar orientations. At any point perpendicular to the final position of the shortest axes of the mineral particles there will be the property of cleavage. As the differential movement at any given place is parallel to the dip, the longest axes of the mineral particles will be in the plane of cleavage and in the direction of dip. The mean axes of the mineral particles will be in the same plane but in the direction of the strike of the cleavage.

If before the folding a cleavage had already developed parallel to the bedding by deep-seated metasomatic change or by flattening parallel to the bedding below the level of no lateral stress, as suggested in the following number of this JOURNAL, this would modify the direction of the secondary structure, making it more nearly parallel to the bedding than it would otherwise be.

In areas of symmetrical or gently inclined folds and in homogeneous rocks the shortening is approximately in the line of the horizon and the cleavage therefore steeply inclined. In heterogeneous rocks the differential movement between the layers, as has been pointed out (pp. 207–208 of my first article), is ordinarily upward for a higher stratum as compared with the one next below it. In the case of abnormal folds (see pp. 330–332 of my second article) this differential movement is emphasized. Consequent upon the differential movement upon the limbs of the fold in weak beds where the shearing motion is largely concentrated, the cleavage is locally flatter than in homogeneous rocks. Whether the rocks are homogeneous or heterogeneous the rotation is in opposite directions on opposite sides of anticlinal arches or synclinal troughs, being outward for an anticline and inward for a syncline; therefore *on opposite limbs of a fold the cleavage usually dips in opposite directions. Upon opposite sides of an anticline the cleavage usually diverges downward, and on opposite sides of a syncline it usually converges downward.*

Ordinarily the rotation of shearing will not go far enough to bring the cleavage into correspondence with bedding, and its dip will be steeper than the dip of the strata; hence, *on opposite sides of a fold the variation in the dip of cleavage is less than the variation in the dip of bedding.* However, in the case of much-compressed normal composite folds (Figs. 8 and 11 on pp. 321 and 323) the force of gravity and unequal thrust control the direction of the moving force, and consequently the form of the secondary folds. In this case the cleavage may be rotated from its ordinary position, and upon opposite sides of the anticlinorium the cleavage may converge downward and upon opposite sides of the synclinorium may diverge downward. This applies as well to the central fan folds as to the minor folds on the flanks (Fig. 9, on p. 321).

It has been pointed out (p. 341) in the case of much-inclined or overturned folds, that the resultant differential movement or shearing between the strata on the steeply inclined or overturned limb may be down for a geologically superior stratum as compared with an inferior stratum. It follows that the shearing on both limbs of the fold is in the same direction, and therefore that *in regions of overturned monoclinal folds the cleavage may be rotated in the same direction throughout, and will hence be monoclinal.* Since on monoclinal folds the differential movement is great on the longer and flatter limb of the fold, the cleavage may be rotated so as to be almost parallel to bedding, but usually is somewhat steeper. As the resultant differential movement is comparatively slight on the steeper, shorter limb, the cleavage usually cuts across the bedding at a considerable angle and is steeper in reference to the horizon. On the opposite limbs of monoclinal fan-shaped anticlines the cleavage may be nearly parallel, or may even converge downward, and on the opposite limbs of monoclinal fan-shaped synclines the cleavage may be nearly parallel, or even diverge downward.

This contrast with symmetrical folds is due to the continuous rotation in the same direction of the cleavage along the arch limb of the fold combined with the rotation in the reversed limb, first opposite to and afterward in the same direction as that on the arch limb. As in the case of symmetrical folds, the variation in dip of cleavage is less than the variation in the dip of bedding. In districts in which cleavage and bedding have the relations above described, on the longer arch limbs it is often difficult to discriminate between the two, but it is believed that the cleavage is usually slightly steeper than the bedding, as already explained. On the steep or reversed limbs the minor crenulations of the strata are usually easily detected intersecting the cleavage.

When rocks are openly folded the discrepancy between cleavage and bedding is usually great. As the folding becomes closer the average discrepancy becomes less. If the compression goes so far as to form isoclinal folds the bedding and cleavage may nearly correspond upon the limbs of the folds, but the two will be at right angles to each other upon the crests of anticlines and in the troughs of synclines (Fig. 7). When the compression is so great as to form plicated folds, the changes in the direction of bedding being very sharp, the discrepancy between bedding and cleavage will be slight. However, the discrepancy is real and important. The cleavage in this case may be about parallel to the axial planes of the folds, and will cut the beds at a very acute angle. In many districts where cleavage has been described as everywhere according with bedding, and the two do approximate but not exactly accord in direction upon the limbs of the folds, a close examination shows that on the crests of the anticlines and in the troughs of the synclines the two structures intersect each other.

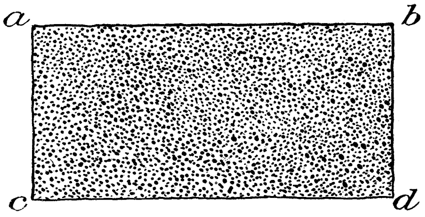

FIG. 8

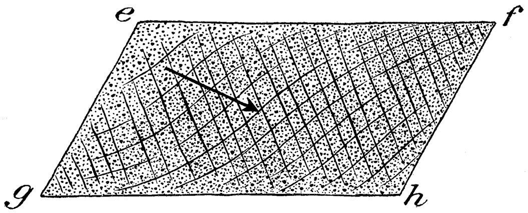

FIG. 9

FIGS. 8 and 9. — Diagram showing development of fissility along the longer and shorter diagonals of a deformed portion of a rock stratum.

In the center of stratum the fractures are in the planes of greatest shearing, but on the outside of the layer the fractures are in lesser shearing planes, the direction of fracture being controlled to some extent by bedding.

At the beginning of the process it may be noted that the shortening is at right angles to the bedding. At the end of the process the shortening is parallel to the bedding. Thus the work first done is partly undone. The resultant position of the shorter axes of the mineral particles in reference to the bed is intermediate between the two extremes.

### DEVELOPMENT OF FISSILITY IN HETEROGENEOUS ROCKS.

The development of fissility in heterogeneous rock beds is still more complicated. The directions of the forces are exactly the same as with cleavage, but as fissility develops along the shearing planes, in the simplest case this structure forms in two general directions. In simple folding, as there is differential movement between the layers, the deformation of a portion of a given layer is that of a rectangle (Fig. 8), *abcd*, into a parallelogram (Fig. 9), *efgh*. If the layer were exactly homogeneous and the pressure normal, the secondary structures would be nearly at right angles to each other and at an angle of about 45° to the greatest pressure. According to Becker, in the case of inclined pressure the structures would have different positions, but they still would be planes. These conditions are most nearly approached in the center of a bed which at this place is massive. However, in passing from the center to the weaker, outer part, the original bedding may largely control the direction of parting, the partings occurring near the planes of bedding rather than in those of greatest tangential stress (Fig. 10). The result is that the planes of fissility may change from their diagonal position in the center of the layer, where it is most rigid, to nearly parallel to the bedding on the outer parts, where it is least rigid.

The diagonal *ad* (Fig. 8) is shortened to *eh* (Fig. 9); therefore the fissility along the diagonal *gf* is formed under conditions of compression. This results in producing many approximately parallel planes of fissility. No sooner does a parting form than the laminæ are sheared over one another, thus producing slickensided surfaces. Across this structure along the longer diagonal, in the plane of the shorter diagonal, there is actual stretching of the material. The length of the original diagonal *cb* is increased to *gf*. Parallel cracks are therefore produced in this direction. As a crack once formed easily widens, the result is the production of a few cracks of considerable size. The broken parts do not rub over one another, and hence do not produce slickensided surfaces. These peculiarities frequently lead to oversight of the shearing along the planes of the shorter diagonal. The development of the cracks along the shorter diagonal are strictly analogous of the upward-pointing crevasses of a glacier.

The planes of fissility near the border of the beds, where the rigidity is less, perhaps originally developed diagonally, may be rotated to a nearly parallel position. This rotation may change the direction of the planes of fissility either in the compressed or the stretched diagonal. The cross fissility will grade into parallel fissility by a gentle curve. On opposite sides of a layer the curves are in opposite directions, just as in the case of cleavage, and by these curves it is easy to determine the relative direction of movement of the layers (Fig. 10).

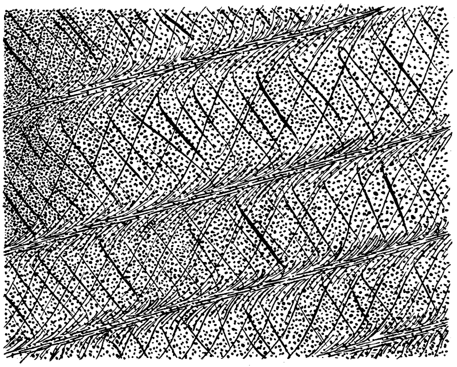

FIG. 10.— Parallel fissility and cross fissility in heterogeneous rock strata.

This rotation is explained by Fig. 11, which is supposed to represent a bed of rock made up of thirteen layers differing in rigidity. In passing from the outside of the bed to the center the coefficient of rigidity of each layer is supposed to be twice as great as that of the one next adjacent. The greatest stress is supposed to be the same throughout the bed, and in an inclined direction, and, as shown (pp. 471–472), these conditions may be approximately complied with upon the limbs of folds. When the differential stress exceeds the ultimate strength of the rock, parallel fractures along shearing planes will be formed. The fracturing will continue until the stress falls below the ultimate strength of the rock. The differential stress may still surpass the elastic limit of the rock, or if not, it may again accumulate until the elastic limit is exceeded. Flowage will then begin.

On account of the varying rigidity the two layers adjacent to the center will have a certain amount of differential movement, which may be called 1. The layers next to them toward the outside will have a movement which would be represented by 2; those next to them, 4; those next to them, 8; and the outside layers a movement of 16. Now, connecting similar points in the different layers, a curve is produced which corresponds very nearly in form to those which have been observed in nature. The structure produced in the diagonal direction, in the centers of the layers, has been rotated to the position indicated. In different rocks the variation of the coefficient of rigidity would be different from that supposed, and it would undoubtedly vary irregularly instead of regularly. A more accurate discussion would consider each of the layers as indefinitely thin, and the coefficient of rigidity in passing toward the center of the bed as increasing by a minute increment. If different numerical suppositions be made, curves would be produced differing from those represented by the figure, but the same in essential character.[1]

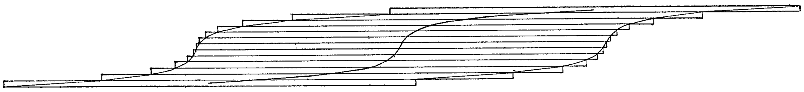

FIG. 11.—Diagram showing rotation of fissility which originally developed in the shearing planes to a position nearly parallel to the bedding.

A third way in which the curved fissility above described may be produced is as a structure secondary to cleavage. That cleavage can be produced having the same curves and relations to bedding as just described for fissility has already been shown (pp. 471–474). Such previously developed cleavage would give parallel curved surfaces of weakness. When the rock passed into the zone of fracture fissility would develop along these shearing planes whether they were those of maximum tangential stress or not.

---

[1] Compare Geology of the Comstock Lode and the Washoe District, by GEO. F. BECKER, Mon. U. S. Geol. Surv., Vol. III, pp. 156–178, 1882.

The above phenomena (probably secondary to cleavage) are finely illustrated in the quartzites of the North Range of Baraboo, Wisconsin and in the massive graywackes of the Ocoee series on the Hiwassee River, Tennessee, combined with cross and parallel secondary structures, as shown by Fig. 10. It is possible that in the cases of both cleavage and fissility as the folding becomes closer and closer the zones of much shearing may extend farther and farther into the rigid beds, producing secondary structures nearly parallel to bedding throughout the limbs of the folds. If the thrust be so powerful as to give the layers isoclinal dips, the secondary structures and bedding will be developed or rotated so as to be nearly parallel throughout the rock-mass, except at the sharp turns on the crests of the anticlines and in the troughs of the synclines, just as in the case of normal plastic flow in homogeneous rocks. (See pp. 464–465).

## RELATIONS OF CLEAVAGE AND FISSILITY TO EACH OTHER.

### GRADATION BETWEEN CLEAVAGE AND FISSILITY.

In passing downward from the zone of fracture to the zone of flowage, one would naturally expect to find all gradations between fissility in two directions developed in the maximum shearing planes and cleavage in a single direction developed in the normal planes. To this natural expectation the phenomena seem to correspond. Rocks are found having two planes of fissility intersecting nearly at 90° ; others which intersect each other somewhat more acutely, so that the rock breaks up into forms having rhombic or rhomboidal sections ; others in which the rhombs or rhomboids have their axes very long in one direction as compared with those in the other ; and others in which the two directions are so nearly parallel that they are not separated, except by close observation.

According to Becker[1] and Hoskins,[2] somewhat inclined intersecting structures may be explained as original developments, but the former places the direction of greatest pressure in the obtuse angle, while the latter, basing his conclusion on experiments, places it in the acute angle made by the two structures. The phenomena may be partly explained by supposing that after the two diagonal structures developed in the shearing planes, the pressure continuing to be applied with a force between the elastic limit and ultimate strength of the rock, there was a rotation of the two sets into approximate parallelism, just as there is when a net with rectangular meshes is pulled out until the intersecting lines are almost parallel. Professor Hoskins offers another explanation of this transition, as follows (*loc. cit.*): In an early stage of the development there may have been flowage of the rock sufficient to produce a more or less perfect cleavage. The rock, as a result of more rapid deformation or of erosion, may then pass to the zone of fracture. If the stresses remain in the same direction the fractures would not take place along planes of greatest shearing stress, but tend to approach the planes of flattening. In proportion as a previous cleavage was prominent, a secondary intersecting fissility in two directions might very nearly approximate in position with the cleavage. Doubtless in many cases the different causes above given combined to produce acutely intersecting fissility.

---

[1] Finite Homogeneous Strain, Flow, and Rupture of Rocks, by GEORGE F. BECKER, Bull. Geol. Soc. Am., Vol. IV, 1893, p. 50.

[2] Flow and Fracture of Rocks as related to Structure, L. M. HOSKINS, Appendix to Principles of North American pre-Cambrian Geology, by C. R. VAN HISE, Sixteenth Ann. Rept. U. S. Geol. Surv., for 1895–6, pp. 872–874.

### FISSILITY SECONDARY TO CLEAVAGE.

For any given layer in a horizontal position in the zone in which fissility is developed, it is probable that horizontal thrust is great in proportion to gravity. If gravity were wholly neglected the greatest shearing stress would be at 45° to the bedding. In the zone in which cleavage is developed it is probable that gravity is very important as compared with tangential thrust. If these are supposed to be equal, the direction of greatest normal pressure would be inclined at 45° to the bedding, and the cleavage planes at right angles to this would also be equally inclined to the bedding, but in an opposite direction. It therefore follows that fissility developing in heterogeneous rocks in the shearing planes and cleavage developing in rocks of the same character in normal planes may have like directions with reference to the bedding. If cleavage be developed in the normal planes inclined to the bedding, and by denudation this stratum passes to the zone of fracture, as a consequence of the lessening power of gravity, these normal planes are now shearing planes, and fissility is controlled in direction by the previous cleavage structure. It thus becomes evident that it may be exceedingly difficult, if not impossible, to discriminate between original fissility in the shearing planes and a secondary fissility which has been controlled by cleavage. In other cases, as well as these special ones, it is to be expected that a rock in which cleavage has developed under deep-seated conditions would be ruptured before reaching the surface during the long time it is in the zone of fracture. To this expectation the facts correspond. In all regions with which I am acquainted having well-developed cleavage, fissility is also found to a greater or lesser degree. Usually the fissility is more marked here and less marked there, for where a fracture or set of fractures has been formed, there it is easier for further movement to occur. Hence belts of strongly fissile rock are separated by others in which there is but slight fissility. In general, however, fractures along shearing planes occur near together or wide apart within all rock-masses showing cleavage. To this the confusion of the two structures is doubtless largely due. It may be that the use of the term "fissility" should be restricted to a structure developing secondary to cleavage or to bedding, and that original fractures, developing along shearing planes, independent of any previous structure, should be called joints. However this may be, it appears probable that where a rock is broken into very thin laminæ in a uniform direction for a considerable area, the secondary structure originally developed as true cleavage in the normal planes. I therefore conclude that *fissility developing in the shearing planes is usually secondary to cleavage which developed in the normal planes.*

## CLEAVAGE AND FISSILITY MAY DEVELOP AT THE SAME DEPTH.

It is clear that in heterogeneous rocks cleavage and fissility may develop in beds of different character at the same depth, for weak beds may be in the zone of flowage at the same depth at which strong beds are in the zone of fracture. For instance, the fine-grained argillaceous beds within a formation may develop cleavage, while the coarser-grained siliceous beds may develop fissility. Thus may be explained some of the cases of change in direction of the secondary structures in passing from one to the other. Also, a bed under a certain weight may be in the zone of fracture if rapidly deformed, and in the zone of flowage if slowly deformed. As has been seen under the subject of deformation (p. 212), the middle zone of combined flowage and fracture is probably 5000 meters thick, and it may be thicker, and throughout this zone either cleavage or fissility may be formed. It is only in the zone of fracture that fissility alone can form, and only in the deep-seated zone of flowage that cleavage alone can form.

C. R. VAN HISE.